Tectonic evolution and paleogeography of Europe

P. O. Yilmaz, I. O. Norton, D. Leary & R. J. Chuchla

Exxon Production Research Co, PO Box 2189,
Houston, TX 77252-2189, USA

ABSTRACT

Multiple rifting and suturing events through Phanerozoic times amalgamated Europe as we know it today. Our detailed analysis of the crustal blocks, now forming of Europe, during the Caledonian, Hercynian and Alpine orogenies, allowed us to understand the influence of these events on the hydrocarbon systems of Europe.

To summarize this, we present a series of 11 palaeogeographic maps from Carboniferous to Pliocene times. These maps were produced as part of a project to develop basin-wide models for regional play element distribution in the major hydrocarbon-producing basins of Europe.

Description of the tectonic evolution of Europe can be divided into four main phases which are related to motions between Baltica, North American/Greenland and Gondwana. The first phase culminated in the assembly of Laurussia (Europe and North America/Greenland) during the Early Palaeozoic Caledonian Orogeny; it was followed by the Carboniferous assembly of Pangea (Laurussia and Gondwana) during the Hercynian orogeny. The third phase, involving rifting and separation of these blocks, started in Permian time. The fourth and final phase, that continues today, is the Alpine orogenic cycle which resulted from convergence of Africa and Europe.

INTRODUCTION

We present a series of palaeogeographic maps which summarizes our understanding of the geologic evolution of Europe since Carboniferous times. These maps were produced as part of an Exxon project to develop basin-wide models for regional play element distribution in the major hydrocarbon-producing basins of Europe.

The tectonic evolution of Europe can be divided into four main phases which are related to motions between Baltica, North American/Greenland and Gondwana. The first phase involved the formation of Laurussia (Europe and North America/Greenland) during the Early Palaeozoic Caledonian Orogeny. The second phase was the Carboniferous assembly of Pangea (Laurussia and Gondwana) during the Hercynian orogeny. The

Yilmaz, P. O., Norton, I. O., Leary, D. & Chuchla, R. J., 1996. — Tectonic evolution and paleogeography of Europe. *In*: Ziegler, P. A. & Horváth, F. (eds), Peri-Tethys Memoir 2: Structure and Prospects of Alpine Basins and Forelands. *Mém. Mus. natn. Hist. nat.*, **170**: 47-60 + Enclosures 1-13. Paris ISBN: 2-85653-507-0.

This article includes 13 enclosures.

third phase was dominated by rifting and separation of these blocks, starting in Permian times. The fourth and final phase continues today and corresponds to the Alpine orogenic cycle which results from convergence of Africa and Europe.

For times younger than Jurassic, relative motions of cratonic blocks were determined from sea floor spreading data in the Atlantic. Motions between Europe and Africa were essentially strike slip from 180 to 110 Ma, then swung round to the convergent motion which continues today. Pre-Jurassic relative plate motions were determined from a combination of palaeomagnetic data and geologic data on the timing of tectonic events. An important final constraint was that the derived relative motions were required to produce a pattern that was geologically reasonable, i.e. no convergent and divergent rates that exceed rates known from global post-Jurassic plate motion rates, and relative motion directions that agreed with the tectonic data. This last constraint is particularly important in the Hercynian orogeny, which includes significant amounts of strike slip motions.

PALAEOZOIC CRUSTAL BLOCKS

Palaeozoic crustal blocks, as they were assembled in Permian times at the end the Hercynian orogeny, are shown in Plate 1. Brief descriptions of these blocks are given below.

Baltica

Baltica, also known as the Russian Platform, is the Precambrian core of Europe; it consists of several Archean age blocks that were amalgamated into cratonic Baltica before 1.6 Ga (Zonenshain et al., 1990). Baltica is bounded on the west by the Iapetus suture and on the east by the Ural suture. The northern edge of Baltica we take to be the Timan Belt and its extension along the northern coast of Scandinavia. This boundary was reactivated during the Late Cambrian Fenno-Scandian orogeny. The southern boundary is less well defined. In Early Palaeozoic time, Baltica faced the Tornquist Sea to the (present day) south. The Tornquist Line itself, however, does not mark the edge of Baltica; the edge is further outboard, buried beneath younger cover (Cocks and Fortey, 1982).

Pechora

This is the crust under the Barents Sea and includes Svalbard. Genesis of this area is poorly understood; we assume it to be amalgamated by the end of the Caledonian orogeny, but most of this block probably consists of older crust.

Laurentia

North America and Greenland are Precambrian cratons that make up the Laurentian block. Like Baltica, Laurentia consists of Archean terranes that were amalgamated during Precambrian times, culminating in the Grenville orogeny between 800 and 1000 Ma.

Avalonia

Avalonia consists of southern England, Ireland and the northeastern seaboard of North America. It rifted away from Gondwana during the Early Cambrian (550 Ma) and was sutured to Laurentia during the Caledonian orogeny (first collision at 425 Ma, end of orogeny at 405 Ma; McKerrow, 1988). There is not enough reliable palaeomagnetic data from Avalonia to determine its positions between rifting and collision. A motion path for it was determined by first plotting the positions of Europe, North America and Africa at the start and end of its motion, then interpolating positions between these times so that the motion of Avalonia was continuous.

Armorica

Armorica is the name for the western Iberian Peninsula and also for what is now western and northern France. Armorica is separated from the rest of France and Iberia (the Southern European Block) by a suture zone of Hercynian age. Structural studies within Armorica indicate that it was severely deformed during the Hercynian orogeny by its collision with the Southern European Block (Matte, 1986), which acted as a solid indentor, wrapping Armorica around itself. Maximum compression of Armorica was 500 km and the axis of maximum deformation forms a line of weakness along which the Bay of Biscay developed in Late Cretaceous times.

Southern Europe

Southern Europe consists of northeastern Iberia, the Balearics, southern France, Corsica and Sardinia and probably some of the Palaeozoic crustal elements involved in the Alps. Like Armorica and Avalonia, this block consists of Pan African affinity crust which rifted off Gondwana during the Early Palaeozoic.

Rhenohercynian

We interpret the Rhenohercynian zone as a zone of Caledonian accretion that was the locus of Devonian extension, as evidenced by the occurrence of bimodal volcanics of Devonian age.

Bohemian Massif

The Bohemian Massif consists of a Precambrian terrane which, according to deep seismic data, must be separated from the Brno-Malopolska Block (Suk et al., 1984).

Brno-Malopolska

The Brno-Malopolska Block is composed of Precambrian granites and metamorphic rocks. This unit includes the southern Holy Cross Mountains area (Malopolska Massif).

Moesia

This block is assumed to consist of some Precambrian crust that was accreted to southern Baltica during the Early Palaeozoic.

Tisza

This block includes crust with European affinity (Royden and Baldi, 1988). It rifted from Europe in Jurassic time, then joined Apulia in colliding with Europe during the Alpine orogeny. Tisza's crystalline and Mesozoic rocks outcrop only near its eastern and western terminations.

PALAEOGEOGRAPHIC MAP FORMAT

The palaeogeographic maps presented here were designed to show depositional environments using the following colours:

Dark brown:	highlands, considered to be sediment source areas.
Light brown:	lowlands, or zones of sediment bypass.
Green:	continental, fluvial and lacustrine.
Yellow:	coastal plain, deltaic to inner shelf.
Teal:	neritic to shelfal.
Light blue:	basin and slope
Blue:	abyssal sediments on either thinned continental or oceanic crust.

Pink and red colours distinguish collision- and extension-related igneous rocks. The only sedimentary lithology shown is a chevron pattern for evaporites. All active structures are indicated using standard symbols as shown on the map legends. Dashed lines show some political boundaries, present-day coastlines are in blue and some geographic zones are identified with letter codes. For orientation purposes, some cities are also shown. Maps are plotted on an Albers equal area projection (standard parallels 44° and 67°) with Europe in its present-day position. A 5° present-day latitude/longitude grid is included, as are palaeolatitude lines derived from a compilation of palaeomagnetic data.

PALAEOZOIC PALAEOGEOGRAPHY

Mid-Carboniferous (Namurian, 322 Ma)

The Mid-Carboniferous (Namurian, Serpukhovian) map, Plate 2, illustrates collision of Armorica and the South-European Block near the end of the Hercynian orogeny. This collisional and magmatic episode was largely ensialic, and resulted in emplacement of abundant synorogenic granites, shown in pink. Widespread orogenic deformations occurred across northern Europe and Iberia and in the Armorican, Saxothuringian, Bohemian, Silesian, Massif Central, Ligerian, Corsica-Sardinia and Carnic Alps areas.

Continental clastics were deposited in the Armorican and Saxothuringian basins; linear basins formed within the collision zone. Flysch was deposited in foredeeps on either side of the main orogenic belt. Principal flysch basins are the Cantabrian Basin in the south, and the Rhenish Basin in the north. The Rhenish Basin was eventually filled to capacity, and by Late Carboniferous time (next time slice) marine connections to this basin were severed.

Upper Carboniferous (Westphalian A/B, 306 Ma)

Hercynian deformation continued into the Late Carboniferous. This final phase of crustal shortening is sometimes referred to as the Variscan phase. Plate 3 shows palaeogeography for the Westphalian A/B stage of the Late Carboniferous. Widespread Variscan deformations consist of thrust- and wrench-faulting, folding, post-tectonic granite emplacement and the accumulation of thick continental sediments in the developing foredeeps. Marine connections to the North-European foredeep basin, located along the northern flank of the Hercynian orogenic belt, were cut off as it progressively filled with clastics. In this basin, thick coal measures were deposited during Westphalian times. These provide the source for most of the gas found in the Rotliegendes sandstones of the Southern Permian Basin. Sedimentation on the South Apulian shelf was locally disrupted by Variscan tectonic events.

Lower Permian (Rotliegendes, 254 Ma)

Lower Permian time was dominated by the collapse of the Hercynian mountain ranges and the deposition of thick clastic sequences in the area of their northern foreland basin. The Rotliegendes (Plate 4) clastic reservoir facies was the first sequence to be deposited. Sedimentation was accommodated partly by thermal subsidence and partly by continued subsidence of the relict Variscan foredeep. This basin is known as the Southern Permian Basin. Possible dextral shear between Gondwana and Europe created intracontinental transform systems creating local transtensional and pull-apart basins. Individually, these faults show relatively small displacements. Grabens along the faults filled with continental clastics. Marine shelf sedimentation continued in the Apulian area.

Upper Permian (Zechstein, 251 Ma)

In Upper Permian time (Plate 5) a marine connection was established between the Arctic shelves and the Northern and Southern Permian basins via the Arctic-North Atlantic rift system (Ziegler, 1988). In the extensive Zechstein inland sea, glacio-eustatic cycles controlled the accumulation of alternating carbonate and evaporite deposits. Late Permian fauna suggest communication between the Boreal Zechstein seas and the Tethys seas via Dobrudgea. Apart from providing halokinetically induced structural traps, the Zechstein evaporites are an important seal facies, which seals the Rotliegendes sands. Further to the south, on the Apulian platform, rifting created basins containing both evaporitic and continental deposits.

MESOZOIC CRUSTAL BLOCKS

Crustal blocks involved in the Mesozoic and Cenozoic Alpine-Carpathian deformation are shown on a Present-Day base map in Plate 6. Europe and Africa remained relatively stable through this time, although older structural grain was reactivated during the Alpine orogeny. Europe and Africa are relatively stable plates to which different crustal blocks were amalgamated through Mesozoic and Cenozoic times. Amalgamation is still going on today with active subduction at the Hellenic trench.

Iberia

The Iberian Block behaved independently of Europe and Africa during the Late Cretaceous and Paleogene (Choukroune et al., 1989; Roure et al., 1989). The cratonic core of the Iberian peninsula consists of Precambrian and Palaeozoic rocks which have undergone Hercynian structuring during the Late Palaeozoic (Pin, 1990; Franke and Engel, 1986; Ziegler, 1988, 1990).

Apulia

Apulia played a key role in the Alpine-Carpathian deformations (Channell et al., 1979; Biju-Duval et al., 1977). The Apulian Block extends from Italy through the Pannonian area, the Adriatic, Greece and further east to Turkey. There is no known pre-Hercynian crust in Apulia. It probably formed as accretionary crust during the Hercynian collision of Gondwana with Europe. Apulian crust was extensively affected by subsequent Mesozoic rifting, until Jurassic separation from Africa eventually led to formation of the Eastern Mediterranean oceanic crust. In Tertiary times, Apulia collided with Europe, initiating the Alpine-Carpathian orogen. During this event, the Apulian Block was shortened and partly subducted. East-dipping subduction formed the Dinaric belt along the eastern margin of Apulia, and west-dipping subduction formed the Apennine belt along its western margin (Royden, 1993; Doglioni, 1992; Casero et al., 1990; Moretti and Royden, 1988; Frasheri et al., Anelli et al., this volume).

Tisza and Moesia

Tisza and Moesia were discussed above in the section on Palaeozoic blocks.

Sakarya

Sakarya is a Cimmerian block which rifted off the northern margin of Gondwana during Late Permian to Triassic times and collided with Europe in Late Triassic to Liassic times (Sengor, 1984; Sengor et al., 1984).

Rhodope

Rhodope is part of Europe. It rifted off Europe but never strayed very far before colliding with the European margin during the Meso-Alpine orogeny (Dixon and Dimitriadis, 1984; Sengor, 1984).

MESOZOIC PALAEOGEOGRAPHY

Upper Triassic (Rhaetian, 210 Ma)

Plate 7 shows Upper Triassic palaeogeography. Triassic times were characterized by regional extension with multidirectional systems of grabens being superimposed on Hercynian structural trends. This extension, known as the Tethyan rift event, had a profound influence on hydrocarbon plays in the Apulian and Carpathian regions. Shallow water reefal limestones characterize rifted margins throughout Apulia. Rifting was accompanied by a widespread extrusive and shallow intrusive volcanism, (Dietrich, 1979; Spray et al., 1984), although individual outcrops are not large enough to be shown on Plate 7. Large areas of northern Europe were affected by Triassic extension, controlling the subsidence of many basins (Plate 7). Generally low Triassic sea levels and narrow rift basins led to highly restricted water bodies and the deposition evaporites (e.g. Muschelkalk, Keuper of northern Europe). During the Triassic, numerous marine connections were established between Tethys and the basins of northern Europe, which, since the Lower Triassic, were separated from the Arctic Seas.

On the Apulian block, a distinctive platform-basin palaeogeography was established by Triassic rifting. Grabens were filled with terrigenous sediments, grading upward into pelagic, cherty carbonates. Platforms localized shallow water carbonates (including reefs) and evaporites. In northern Italy, Middle Triassic to Carnian volcanics and massive reefs outcrop in the Dolomites. In the Adriatic and Central Apennine areas, shallow water evaporites (e.g. Burano formation) were deposited, while deep-water clastics (e.g. Riva di Solto formation) characterized the Northern Apennines and Po Basins. Both the Burano and Riva di Solto formations include source-rock facies (Anelli et al., this volume). During Late Triassic times, possible initial opening of the Vardar ocean occurred. This marked the first formation of post-Hercynian oceanic crust in the study area (Spray et al., 1984; Dietrich, 1979).

In northern Apulia, distinct transverse zones, following Hercynian trends, were established. These zones were manifested as a series of flexures which delimited domains of platform/basin geometry.

During Late Triassic times, long-standing south-directed subduction of the Palaeo-Tethys ocean along the northern margin of the Cimmeria blocks terminated with their collision with Europe (Sengor, 1984; Sengor et al., 1984). In Europe, Cimmerian deformations of Late Triassic and Early Jurassic age is documented by unconformities in the Polish Trough, the Northern Po Basin, and in the Italian Dolomites.

Along the African margin, Ladinian to Carnian age extensional tectonics created half-grabens and pull-apart basins in the High Atlas trough. This trend followed an aborted Late Carboniferous to Permian rift (Cousminer and Manspeizer, 1977). During the Late Triassic and Early Jurassic, the newly created grabens were filled with continental and evaporitic sediments. Further west in Morocco, grabens were associated with continental clastics and alkaline volcanism (Wildi, 1983).

Early Jurassic (Toarcian, 179 Ma)

During Early Jurassic times the Tethyan rift system remained active (Biju-Duval et al., 1977; Dewey et al., 1973; Dercourt et al., 1986; Ziegler, 1988, 1990). Plate 8 shows palaeogeography for the Toarcian stage of the Early Jurassic. This was also the time of initiation of opening of the Central Atlantic between North America and Africa; with this a sinistral strike-slip regime was established between Africa and Europe. At this time marine connections were reopened between the Arctic Seas and the Tethys Ocean via the Arctic-North Atlantic rift (Ziegler, 1988). Continued tectonic subsidence of the Tethyan and European rift systems, combined with a eustatic sea level rise, open oceanic circulation patterns and low palaeolatitudes favoured deposition of widespread carbonate platforms, especially on Apulia. In the Briançonnais area (#4 on Plate 8), rifting caused foundering of the older Middle to Upper Triassic platforms, on which shallow water carbonates had been deposited (Rudkiewicz, 1988; Michard and Henry, 1988).

In the Helvetic realm, sedimentation was dominated by carbonates grading into marly sequences (Funk et al., 1987). In Lias and Dogger times, sedimentation consisted of mainly shales (Dauphinois facies). Rapid horizontal facies changes and wide stratigraphic gaps characterize this facies (Masson et al., 1980). Rifting in the Eastern Mediterranean resulted in formation of oceanic crust in the Antalya area (# 2 on Plate 8; Robertson and Dixon, 1984; Yilmaz, 1984).

Along the Cimmerian collision zone (#1 on Plate 8), flysch deposition occurred in Dobrudgea, Crimea and Northern Turkey (Sengor, 1984). Cimmerian orogenic activity terminated in Early Jurassic times, as evidenced by intrusion of Middle Jurassic plutons on both sides of the suture. Effects of this event were also felt in the Polish Trough, and local inversion occurred in the Donets Trough.

The Iberian Meseta was an important source of clastics in the Cantabrian Basin, Lisbon and Cavalla basins and also the Duero Basin (Wildi, 1983; Ziegler, 1988). Scattered extensional magmatism occurred on the Iberian Meseta and also in the Pyrenees area.

Along the African margin, tilting and foundering of fault-blocks occurred mainly during the Sinemurian and thus is slightly older than the time represented on Plate 8 (Favre and Stampfli, 1991).

Middle Jurassic (Bathonian, 158.5 Ma)

The Bathonian map (Plate 9) shows the onset of sea floor spreading in the Central Atlantic. This spreading system continued to the north between Iberia and Africa and then bifurcated into two branches, one between Apulia and Europe and one between Apulian and Africa. Continuation of the northern branch past the Tisza and the Pienniny area into the Black Sea is speculative; this is based on occurrence of rifting in the Magura Trough and

Mecsek Zone and provides a mechanism for the formation of the Transylvanian ophiolites.

In the Helvetic domain, sedimentation patterns indicate progressive starvation and deepening of the basin: Middle Jurassic manganese oozes are succeeded by Late Jurassic radiolarites, Tithonian Calpionellid oozes, slump deposits and transported turbiditic calcarenites. In the Tethys area, a global high-stand led to widespread carbonate platform development. Pelagic sediments were deposited in troughs while shallow water carbonate sedimentation appears to have kept pace with subsidence on the platforms, continuing the distinctive basin/platform topography of Apulia. Carbonate platforms in the Dinaric and Friuli areas supplied large amounts of debris into the Belluno Basin (Massari et al., 1983). Apulian carbonate platforms reached their maximum extent in Cretaceous time.

Late Jurassic-Earliest Cretaceous

We do not have palaeogeographic maps covering Late Jurassic and earliest Cretaceous times. Some of the major tectonic events are briefly summarized here.

Late Jurassic to Early Cretaceous tectonic development of southern Europe was primarily controlled by opening of the Central Atlantic which established a regional sinistral shear between Africa and Europe. Apulia rotated in a counter-clockwise direction, opening the Mediterranean until Mid-Cretaceous times, when it became fixed to Africa (Dewey et al., 1973; Bernoulli and Lemoine, 1980; Biju-Duval et al., 1977; Channell et al., 1979). Several ophiolitic suites (e.g. Liguride, Piedmont, Transylvanian and Vardar) were formed by these spreading events.

A Late Jurassic subduction zone with calc-alkaline volcanism and flysch sedimentation formed along the Dinaric shelf margin of Apulia (Frasheri et al., this volume). Faunal evidence from the Mecsek and Villany-Bihor areas on the Tisza platform and the Briançonnais zone of the Alps (Roux et al., 1988) indicates that these areas were linked until Tithonian times and but were separated afterwards. This indicates decoupling of the Tisza block in Tithonian time. We suggest that Tisza separated from Europe in Tithonian times and subsequently became attached to Apulia before again colliding with Europe in Eocene times.

Lower Cretaceous (Aptian, 112 Ma)

By Mid-Cretaceous times, Atlantic sea floor spreading had propagated northward between Iberia and North America and Iberia started to separate from Europe (Plate 10). Mediterranean sea floor spreading was nearly complete. Motions between Africa and Europe, which were sinistral from Jurassic through Early Cretaceous times, changed in Mid-Cretaceous times to progressively more convergent, with the convergence direction becoming almost normal to the European margin by Eocene times as the Arctic-North Atlantic opened. This convergence established the Alpine orogeny as well as several other, more localized compressional events. One of these was in the Rhodope area, with compressional deformation and flysch deposition along the southern margin of the Moesian Platform. Compression also occurred along the eastern margin of Golija and on the Pelagonian Platform. During Early Cretaceous times, Pelagonia collided with Rhodope and emplacement of nappes took place in the Hellenides and Dinarides.

In Iberia and the Aquitaine Basin, block tilting associated with extensional tectonics as well as halokinetic movements of Triassic evaporites took place during Early Cretaceous times (Le Vot et al., this volume). In the Western Alps, collision started during Cenomanian-Early Senonian time due to subduction of the European margin south or south-east beneath the Apulian margin; this is evidenced by blueschists and eclogites (Debelmas, 1989). The suture is seen in the Canavese slices (schistes lustres) and Sesia zone. High pressure metamorphism associated with the suturing event has been dated at 130 Ma and also 100-80 Ma (Debelmas, 1989). Upper Jurassic -Lower Cretaceous ophiolite-bearing, highly deformed nappes are overlain by Upper Cretaceous relatively undeformed flysch nappes, indicating the beginning of European-African compression in the Albian. Intra-Apulian deformation was localized along pre-existing lines of weakness, principally Permo-Triassic grabens. An east-dipping subduction zone initiated in front of the Golija and Pelagonian platforms. During the Late Cretaceous, major tectonic movements affecting the Austro-Alpine domain, the internal Dinarides.and the Southern Alps are expressed by a transition from flysch sedimentation in the Lombardian and Julian-Slovenian basins to a pelagic setting in the Belluno basin and Trento platform (Massari et al., 1983).

In the Apuseni mountains, Albian thrusting and folding, along with flysch sedimentation, indicates that the Tisza block collided with or was close to Apulia by Middle Cretaceous times (Burchfiel, 1980). By Late Cretaceous times, large strike-slip movements dominate the Tisza block and North Pannonian part of the Apulian block as the two blocks impinged on the Carpathian embayment. This deformation is also expressed in the Eastern Alps by lateral extrusion structures (Ratschbacher et al., 1991). Further to the east, a north-dipping subduction zone, characterized by magmatic activity and back-arc rifting, was established in the present Black Sea (Gorur, 1989).

Counter-clockwise rotation of Iberia relative to Europe resulted in sinistral shear along the North Pyrenean fault zone (Galdeano et al., 1989; Choukroune et al., 1989; Roure et al., 1989). Oceanic crust developed in the Bay of Biscay following early Aptian separation between Galicia Bank and Flemish Cap (Dewey et al., 1973; Ziegler, 1988, 1990). Rifting movements decreased considerably in the East-Iberian Basin during Cretaceous time, with continental to deltaic sandstone deposition. In addition to the Pyrenean area, shear deformation took place in the Cantabrian Mountains of northern Spain and in the Celt-Iberian Range in central Spain. The nature of this shear was predominantly transtensional and was manifested in the form of rifts and pull-apart basins. Post-rift deposition began during late Aptian-Albian time. A thick sequence of shallow water, interbedded clastics and carbonates accumulated on the subsiding Atlantic margin.

The Late Cretaceous was characterized by the same opposed evolution of a shallow carbonate platform in the eastern Iberides and a deep, terrigenous flysch basin in the western Pyrenees. During Mesozoic times, both on the platforms and in the basins, the depositional sequence organization was closely linked to eustatic sea level changes. Local extensional processes generated important modifications in thickness, particularly within the Lower Triassic, Liassic, Kimmeridgian and Aptian series, as well as within the Pyrenean Mid- and Upper Cretaceous deposits. By the early Campanian, sea floor spreading ceased in the Bay of Biscay and Iberia began to converge with Europe. In the eastern Pyrenees, the main deformation was Santonian and Campanian. The Pyrenean collision front propagated westward during late Senonian to Palaeocene time.

CENOZOIC PALAEOGEOGRAPHY

Lower Oligocene (Rupelian, 33.5 Ma)

Plate 11 shows palaeogeography for lower Oligocene times. This was a period of intense tectonic activity following the collision of the Apulian and European blocks. This collision was the result of continued convergence between Africa and Europe. The Apulia-Europe collision was diachronous, starting north of the present-day Adriatic and propagating eastward into the Carpathians and westward toward the Western Alps. Extensive deformation, metamorphism, plutonic activity and deposition of thick flysch and molasse sequences occurred along the entire deformation front.

In the Alps, initial deformation occurred in the Piemont, Briançonnais and Valais zones with later involvement of the Ultrahelvetic and locally the Helvetic domains. Development of the Molasse Basin accompanied this deformation phase (Ziegler et al., this volume). Northward transgression of the Tethys sea led to a progressive onlap of Cenozoic rocks onto the basal Tertiary unconformity (Roeder and Bachmann, this volume). Local positive features in the foreland persisted until Oligocene time when the basin deepened rapidly (Bachmann et al, 1987). Rising sea levels and local restricted circulation provided ideal conditions for the accumulation of very rich source-rocks (e.g. Fish Shales formation in the Molasse Basin).

Alpine deformation was coeval with orogenic activity along the Apennine and Dinaric fronts. Initial deformation of the palaeo-Apennine chain started during Oligocene times with thrusting of the Liguride oceanic and flysch units (#2 on Plate 11). Deformation and flysch sedimentation were controlled by the palaeotectonic framework inherited from Mesozoic tectonics. The shape and interrelations of different basins varied as the structural framework became better defined. The Apennine depocenters shifted from south to north as different structural units deformed. The amount of deformation increases from the north to the south (Bally et al, 1986). This areal distribution of deformation controls trap size and trap integrity (Anelli et al., this volume).

During Eo-Oligocene time, the Apulian promontory pushed the North Pannonian and Tisza blocks into the Pannonian embayment (Plate 11). Together they "escaped" into this embayment, which existed as a gap between the buttresses of the Bohemian Massif to the northwest and the Moesian platform to the southeast. In this process, the North Pannonian and Tisza blocks pushed the flysch, which had been deposited in front of the inner, crystalline part of the Carpathians, over the Carpathian foreland (#1 on Plate 11). The flysch was folded and thrusted, accommodating at least 200 km of shortening. Loading of the foreland and a coincident high stand in sea level provided ideal conditions for the accumulation of widespread, very rich Oligocene source-rocks in the region of the Carpathian fold-and-thrust belt (e.g. Dysodilic and Menilitic shales; see Bessereau et al., Dicea, this volume).

Compressional deformation of the Alps and their foreland was contemporaneous with the evolution of the intracratonic Rhine, Bresse, and Rhône rifts (Ziegler, 1987, 1990; Ziegler and Roure, this volume). A pulse of volcanism may have triggered extension in the Rhine Graben during the late Eocene (#4 on Plate 11). By late Eocene-early Oligocene times, a marine connection was established between the Alpine foredeep and the North Sea via the Rhine Graben in which the Fish Shales formation was deposited, the source-rock for most of the hydrocarbon accumulations in this graben.

Continued convergence of Iberia with Europe caused westward propagation of the Pyrenean deformation front into the Cantabrian region. During the Eocene main Pyrenean deformation phase Iberia was sutured to Europe (Roure et al., 1989; Chouckroune et al., 1989; Ziegler, 1988, 1990).

Tethys ocean crust subduction continued in the Alboran-Corsica/Sardinia region (#5 on Plate 11). Back-arc rifting behind this northwest-dipping subduction zone separated the Balearic Islands, Kabyl, Alboran and Corsica/Sardinia blocks from Europe (Torné et al., Vially and Trémolières, this volume).

Middle Miocene (Serravallian, 10.5 Ma)

Miocene Alpine deformation strongly affected several parts of the orogenic belt (e.g. Central, Western and Southern Alps, Carpathians, Apennines, Plate 12). In the Molasse Basin, with falling sea levels and increasing influx of clastics from the rapidly advancing Alpine orogenic front, the basin shallowed and a thick continental molasse section was deposited (Roeder and Bachmann, this volume).

During Middle Miocene time, back-thrusting of the Southern Alps accompanied deformation along the Dolomites (Doglioni, 1991, 1992; Ziegler et al., this volume). These thrusts involved the Apulian Mesozoic platform and raised the northern Po area (#3 on Plate 12). In the southern Po area, local emergence and evaporite deposition (e.g. Gessosso Solfifera formation) occurred. Active west-dipping subduction in the Apennine region and development of an east-facing foredeep took place, recorded by the Macigno flysch (Anelli et al., this volume). Flysch sedimentation from both the Apennine and Albanian accretionary complexes created the Po/Adriatic basin as a bivergent foredeep area. The main thrusting event in the Apennines occurred during the Miocene. These thrusts utilized Triassic evaporite layers as detachment surfaces (D'Argenio et al., 1980, Boccaletti and Coli, 1982). Tortonian continental and lacustrine sediments, unconformably overlying flysch facies, record this event, thereby constraining the timing of the end of the main deformation phase. On the east side of the Adriatic, subduction of the relict Tethyan ocean continued along the Albanian and Hellenic subduction boundary (#2 on Plate 12).

The Carpathian foredeep expanded over the European margin as the deformation front migrated to the East- and South-Carpathians (#4 on Plate 12). Rapid advance of the thrust front caused the Oligocene source section to be uplifted and maturation of the rich source facies terminated. Therefore, over large areas, Oligocene source-rocks are only mature where they have been structurally buried in the thrust belt or buried by sediments in the very proximal parts of the foredeep (Bessereau et al., Ziegler and Roure, this volume). Volcanism around the Carpathian arc, related to this phase of deformation, began during the late Oligocene and is thought to be related to the subduction of highly attenuated European continental crust beneath the overriding Carpathians. Back-arc extension began in the Pannonian basin during this time. By the end of the Miocene, deformation had stopped in all but the Romanian portion of the Carpathians (#5 on Plate 12).

By early Miocene time, the marine connections through the Rhine, Leine, and Eger grabens were severed as a result of uplift of the Rhenish Massif and Massif Central. Tectonism in these grabens, in which as much as 3 km of continental sediments were deposited, continued, as shown by volcanic activity.

Corsica/Sardinia and the Kabyl blocks were separated from Europe during the early Miocene (23 to 19 Ma; #1 on Plate 12; Vially and Trémolières, this volume). This motion was a primary driver for deformation of the Apennines. Fault blocks formed by rifting in the Valencia Trough contain the largest oil play found to date in Spain (Torné et al., this volume).

The Late Miocene was characterized by compression along the southeastern margin of Iberia in the Prebetic fold belt and in portions of the Balearic Islands. Westward escape of the Alboran Block opened the North Algerian Basin in its wake. The Alboran Block collided with the southeastern margin of Iberia and the northwestern margin of Africa during the late Oligocene/early Miocene. Extensive flysch basins mark this Betic/Rif deformation front (the Numidian flysch of Wildi, 1983; Ziegler, 1988). The Kabyl block escaped southwards and collided with North Africa to form the Tellian mountains of Algeria and Tunisia (Wildi, 1983).

During the late Tortonian, Calabria rifted from the Corsica and Sardinia block, creating the Tyrrhenian Sea as a back-arc rift basin.

Lower Pliocene (3.8 Ma)

During Pliocene time, development of ocean crust in the Tyrrhenian Sea was accompanied by extensive magmatism (Channell and Mareschal, 1989, #1 on Plate 13). This was synchronous with Pliocene Apennine nappe emplacement. Shortening in the Apennines (75 km in the north, 150 km in the south; Bally et al, 1986) was balanced by extension in the Tyrrhenian Sea (Doglioni, 1991). Extension initiated in late Tortonian time in the Apennine hinterland, creating small rift basins filled with Neogene clastics, sitting piggyback-style on the thrust belt (Boccaletti and Coli, 1982). The Apennine foredeep shifted northwards as the Liguride thrust belt was reactivated during the Pliocene. The Pliocene section, 9 km thick, consists of shallow water fluviatile sediments (#4 on Plate 13). Tertiary biogenic gas plays are found in this foredeep (Anelli et al., this volume). The dramatic subsidence in this foredeep can not be explained alone by the topographic load of the Apennine thrust sheets (Royden and Karner, 1984; Royden, 1993).

In the Alps, the most significant deformation is in the Helvetic domain. The deformation front continued to progress to the north, leading to late Miocene and early Pliocene folding and thrusting of the Jura Mountains. Peak deformation was during the latest Pliocene. The thrust decollement in the Jura is located in the Triassic evaporite section which continues to the south under the Molasse Basin and eventually under the Alps. The Molasse Basin was carried passively to the north (as a "piggy-back" basin) during this part of its history (Philippe et al., Ziegler et al., this volume). By the end of Tertiary times an approximately 5 km thick section of synorogenic clastics had accumulated in this basin.

Deformation continued in the outermost East- and South-Carpathians. Extremely rapid subsidence in the East-Carpathian foredeep occurred during Mio-Pliocene time with accumulation of approximately 9 km of coarse clastic molasse sediments. The East-Carpathian foredeep is intensely deformed to the west where it is partially overridden by thrusts of the flysch zone. To the north, this inner zone, which consists mainly of the lower molasse, is deformed by thrusts and folds. Salt appears to act as a detachment surface but is also involved in folding as salt diapirs pierce some of the folds and salt is locally squeezed up along thrust faults. This section contains the giant fields of the Ploesti district (in the area of SCF on Plate 13; Dicea, this volume).

The dramatic subsidence in the East-Carpathian foredeep can not be explained by the modest topographic load of the Carpathian Mountains (Royden, 1993, Doglioni, 1992). Royden (1993) suggests that the Carpathians are an example of a retreating subduction boundary where overall plate convergence is less than the rate of subduction. The deficiency in plate convergence was compensated by extension in the Pannonian back-arc basin. Regional extension continues today as seen in high grade metamorphic rocks of mid-crustal origin which are exposed in Rechnitz window and in Hungary (Tari, 1991).

The Carpathians are tectonically active today with activity largely restricted to the area of the Carpathian bend, also known as the Vrancea seismic zone. Large earthquakes with very deep hypocenters and compressional to strike-slip fault plane solutions typify this area; these may be produced by the leading edge of the (detached) downgoing slab under the Carpathian arc.

CONCLUSIONS

In this study, we utilized the plate tectonic history of Europe to constrain the understanding of sedimentary basin development and the effects of regional scale tectonic events on play elements for major basins. The tectonic framework and palaeogeography were used as constraints on models for basin formation, climate distribution and accommodation space which, in turn, control the distribution of reservoirs, source-rocks, seals and traps.

The structural and stratigraphic framework of Europe is the result of its Phanerozoic tectonic history, involving the amalgamation of crustal blocks. Multiple rifting and collision events created extremely complex mountain systems during the Caledonian, Hercynian, Cimmerian and Alpine orogenies. Basins are diverse, superimposed, have long-lived tectonic histories with complex structuring, and have highly variable play elements. The Hercynian orogen provides the framework for North European hydrocarbon systems. Its collapse sets up the Apulian Mesozoic hydrocarbon system. Alpine deformation and tectonically related extension, in turn, set up the Neogene hydrocarbon systems of the Carpathians, Pannonian Basin and the Apennines (Ziegler and Roure, this volume)

Acknowledgments- We thank *Exxon Production Research Company (EPR)* and *Exxon Exploration Company (EEC)* for permission to publish this paper. Also, we express our special thanks to *EPR-Geoscience* for funding of this publication. Hoa Tran of *EEC* drafted all the maps. We wish to thank the other members of the *European Regional Study Team* for their contributions: R. S. Bishop, H. M. Bolas, L. B. Cauffman, S. Gardiner, D. Gilbert, M. H. Feeley, J. L. Hagmaier, P. M. Haller, M. T. Ingram, S. D. Knapp, R. A. Kolarsky, D. W. Mason, R. T. Mooney, J. A. Newhart, G. J. Nolet, L. S. Smith and J. P. Verdier. This manuscript benefited from earlier reviews by Mike R. Hudec. We thank Peter Ziegler for inviting us to contribute to this volume.

REFERENCES

Bachmann, G.H., M. Müller and K. Weggen (1987), Evolution of the Molasse Basin (Germany, Switzerland). In *Compressional Intra-Plate Deformations in the Alpine Foreland* (Edited by Ziegler, P.A.). *Tectonophysics*, **137**, pp. 77-92.

Bally, A.W., L. Burbi, C. Cooper and R. Ghelardoni (1986), "Balanced sections and seismic reflection profiles across the central Apennines". *Mem. Soc. Geol. It.*, **35**, pp. 257-310.

Bernoulli, D. and M. Lemoine (1980), Birth and early evolution of the Tethys: the overall situation. In *Geology of the Alpine Chains Born of the Tethys* (Edited by Aubouin, J., J. Debelmas and M. Latreille). *Aubouin. Bur. Rech. Geol. Min., Mem.* **115**, pp. 168-179.

Biju-Duval, B., J. Dercourt and X. Le Pichon (1977), From the Tethys Ocean to the Mediterranean Seas: a plate tectonic model of the evolution of the Western Alpine System. In *International Symposium on the Structural History of the Mediterranean Basins* (Edited by Biju-Duval, B. and L. Montadert). Ed. Technip, Paris, pp. 143-164.

Boccaletti, M. and M. Coli (1982), *Carta Strutturale Dell'Apennino Settentrionale*, C.N.R. Publ. 429, Firenzi, Scale: 1:250,000.

Burchfiel, B.C. (1980), *Geology of Romania*. Geol. Soc. Am. *Spec. Paper*, **158**, 82 p.

Casero, P. et al. (1990), Neogene geodynamic evolution of the Southern Apennines. In *Petroleum and Tectonics in the Apennines and Sicily*. IFP 38195, Part II.

Channell, J.E.T. and J.C. Mareschal (1989), Delamination and asymmetric lithospheric thickening in the development of the Tyrrhenian rift. In *Alpine Tectonics* (Edited by Coward, M.P., D. Dietrich and R.G. Park). *Geol. Soc. Am. Spec. Publ.*, **45**, pp. 285-302.

Channell, J.E.T., B. D'Argenio and F. Horvath (1979), "Adria, the African promontory, in Mesozoic Mediterranean palaeogeography". *Earth-Sci. Rev.*, **15**, pp. 213-292.

Choukroune, P., M. Daignieres, J. Deramond, J.R. Grasso et al. (1989), "The Ecors Pyrenean deep seismic profile reflection data and the overall structure of an orogenic belt". *Tectonics*, **8**, pp. 23-39.

Cocks, L.R.M. and R.A. Fortey (1982), "Faunal evidence for oceanic separations in the Palaeozoic of Britain". *J. Geol. Soc., London*, **139**, pp. 465-478.

Cousminer, H.L. and W. Manspeizer (1977), Autunian and Carnian palynoflorules: contribution to the chronology and tectonic history of the Moroccan Pre-Atlantic Borderland. In *Stratigraphic Micropaleontology of Atlantic Basin and Borderlands* (Edited by Swain, F.M.). *Develop. in Paleon. and Stratigr.*, Ser. 6, pp. 185-204.

D'Argenio, B., F. Horvath and J.E.T. Channell (1980), Palaeotectonic evolution of Adria, the African promontory. In *Geology of the Alpine Chains Born of the Tethys* (Edited by Aubouin, J., J. Debelmas and M. Lateille). Bur. Rech. Geol. Min., *Mem.* **115**, pp. 331-351.

Debelmas, J. (1989), On some key features of the evolution of the Western Alps. In *Tectonic evolution of the Tethyan region* (Edited by Sengor, A.M.C., Y. Yilmaz, A.I. Okay and N. Gorur). NATO Advanced Study Inst. Ser. C, **259**, pp. 23-42.

Dercourt, J., L.P. Zonenshain, L.-E. Ricou, V.G. Kazmin et al. (1986), Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. *In Evolution of the Tethys* (Edited by Aubouin, J., X. Le Pichon and A.S. Monin). *Tectonophysics*, **123**, pp. 241-315.

Dewey, F., C. Pitman, B.F. Ryan and J. Bonnin (1973), "Plate tectonics and the evolution of Tethys; with discussion". *Rapp. Comm. Int. Mer Mediter.*, **22**, pp. 72-75.

Dietrich, V.J. (1979), "Ophiolitic belts of the central Mediterranean". Geol. Soc. Am., Map Chart Ser. MC-33, pp. 5-9.

Dixon, J.E. and S. Dimitriadis (1984), Metamorphosed ophiolitic rocks from the Serbo-Macedonian massif, near Lake Volvi, north-east Greece. In *The Geological Evolution of the Eastern Mediterranean* (Edited by Dixon, J.E. and A.H.F. Robertson). *Geol. Soc., London, Spec. Publ.* **17**, pp. 603-618.

Doglioni, C. (1991), *Escursione nel Sudalpino orientale (Dolomiti e Prealpi Venete)*. AGIP, 92 p.

Doglioni, C. (1992), "Main differences between thrust belts". *Terra Nova*, **4**, pp. 152-164.

Doglioni, C. (1992), The Venetian Alps thrust belt. In *Thrust Tectonics* (Edited by McClay, K.R.). Chapman and Hall., London, pp. 319-324.

Favre, P., and G. Stampfli (1991), "Riftogenesis in the Alps and central Atlantic: a comparison". *Terra Abstracts*, **3**, pp. 217.

Franke, W. and W. Engel, W. (1986), "Synorogenic sedimentation in the Variscan Belt of Europe". *Bull. Soc. géol. France*, **8**, 2, pp. 25-33.

Funk, H., R. Oberhänsli, A. Pfiffner, S. Schmid et al. (1987), "The evolution of the northern margin of Tethys in eastern Switzerland". *Episodes*, **10**, pp. 102-106.

Galdeano, A., M.G. Moreau, P.Y. Berthou, J.A. Malod et al. (1989), "New paleomagnetic results from Cretaceous sediments near Lisboa (Portugal) and implications for the rotation of Iberia". *Earth Planet. Sci. Lett.*, **92**, pp. 95-106.

Gorur, N. (1989), Timing of opening of the Black Sea: sedimentological evidence from the Rhodope-Pontide fragment. In *Tectonic Evolution of the Tethyan Region* (Edited by Sengor, A.M.C., Y. Yilmaz, A.I. Okay and N. Gorur). NATO Advanced Studies Inst. Ser. C, No. **259**, pp. 131-136.

Massari, F., F. Medizza and J.E.T. Channell (1983), "Santonian to Maastrichtian stratigraphy of some pelagic limestone sections of the Venetian Alps (northern Italy)". *Newsletters on Stratigr.*, **12**, pp. 18-28.

Masson, H., R. Herb, A. Steck, D. Aubert et al. (1980), Excursion No. 1; Helvetic Alps of Western Switzerland. In *Geology of Switzerland; a guide-book. Part B) Geological excursions.* Wepf & Co., Publ., Basel, pp. 109-153.

Matte, P. (1986), Tectonics and plate tectonics model for the Variscan Belt of Europe. In *Structure of Pre-Alpine Orogenes* (Edited by Giese, P. and H.J. Zwart). *Tectonophysics*, **126**, pp. 329-374.

McKerrow, W.S. (1988), The development of the Iapetus Ocean from the Arenig to the Wenlock. In *Caledonian Appalachian Orogen* (Edited by Harris, A.L. and D.J. Fettes). *Geol. Soc., London, Spec. Publ.* **38**, pp. 405-412.

Michard, A. and C. Henry (1988), "Les nappes briançonnaises en Haute-Ubaye (Alpes franco-italiennes); contribution a la reconstitution paleogeographique du Briançonnais au Mesozoique (The Briançonnais nappes in the Ubaye Valley, French-Italian Alps; a contribution to the paleogeographic reconstruction of the Briançonnais domain during the Mesozoic)". *Bull. Soc. géol. France*, 8, IV, pp. 693-701.

Moretti, I. and L. Royden (1988), "Deflection, gravity anomalies and tectonics of doubly subducted continental lithosphere: Adriatic and Ionian Seas". *Tectonics*, **7**, pp. 875-893.

Pin, C. (1990), Variscan oceans: ages, origins and geodynamic implications inferred from geochemical and radiometric data. In *Terranes in the Variscan Belt of Europe and Circum-Atlantic Paleozoic Orogens* (Edited by Matte, Ph.). *Tectonophysics*, **177**, pp. 215-227.

Ratschbacher, L., W. Frisch, H.-G. Linzer and O. Merle (1991), "Lateral extrusion in the Eastern Alps, Part 2: Structural analysis". *Tectonics*, **10**, pp. 257-271.

Robertson, A.H.F. and J.E. Dixon (1984, Introduction: aspects of the geological evolution of the Eastern Mediterranean. In *The Geological Evolution of the Eastern Mediterranean* (Edited by Dixon, J.E. and A.H.F. Robertson). *Geol. Soc., London, Spec. Publ.* **17**, pp. 1-74.

Roure, F., P. Choukroune, X. Berastegui, J.A. Munoz et al. (1989), "ECORS deep seismic data and balanced cross sections: geometric constraints on the evolution of the Pyrenees". *Tectonics*, **8**, pp. 41-50.

Roux, M., J.-P. Bourseau, T. Bas, T. Dumont et al. (1988), "Bathymetric evolution of the Tethyan margin in the western Alps (data from stalked crinoids): a reappraisal of eustatism problems during the Jurassic". *Bull. Soc. géol. France*, **8**, IV, pp. 633-641.

Royden, L.H. (1993), "The tectonic expression of slab pull at continental convergent boundaries". *Tectonics*, **12**, pp. 303-325.

Royden, L.H. and T. Baldi (1988), Early Cenozoic tectonics and paleogeography of the Pannonian and surrounding regions. In *The Pannonian Basin: A Study in Basin Evolution* (Edited by Royden, L.H. and F. Horvath). Am. Assoc. Petrol. Geol., *Mem.* **45**, pp. 1-16.

Royden, L. and G.D. Karner (1984), "Flexure of lithosphere beneath Apennine and Carpathian foredeep basins: evidence for an insufficient topographic load". *Am. Assoc. Petrol. Geol., Bull.* **68**, pp. 704-712.

Rudkiewicz, J.-L. (1988), "Quantitative subsidence and thermal structure of the European continental margin of the Tethys during early and middle Jurassic times in the western Alps (Grenoble-Briancon transect)". *Bull. Soc. géol. France*, **8**, IV, pp. 623-632.

Sengor, A.M.C. (1984), *The Cimmeride Orogenic System and the Tectonics of Eurasia.* Geol. Soc. Am., Spec. Paper 195, 89 p.

Sengor, A.M.C., Y. Yilmaz and O. Sungurlu (1984), Tectonics of the Mediterranean Cimmerides: nature and evolu*tion of the western termination of palaeo-tethys. In The Geological Evolution of the Eastern Mediterranean* (Edited by Dixon, J.E. and A.H.F. Robertson). *Geol. Soc., London, Spec. Publ.* **17**, pp. 77-112.

Spray, J.G., J. Bebien, D.C. Rex and J.C. Roddick (1984), Age constraints on the igneous and metamorphic evolution of the Hellenic-Dinaric ophiolites. In *The Geological Evolution of the Eastern Mediterranean* (Edited by Dixon, J.E. and A.H.F. Robertson). *Geol. Soc., London, Spec. Publ.* **17**, pp. 619-627.

Suk, M., M. Blizkovsky, T. Buday, I. Chlupac et al. (Eds.), 1984), *Geological History of the Territory of the Czech Socialist Republic.* Geol. Survey, Prague, Academia Publ. House, Prague, 396 p.

Tari, G. (1991), "Multiple Miocene block rotation in the Bakony Mountains, Transdanubian Central Range, Hungary". *Tectonophysics*, **199**, pp. 93-108.

Wildi, W. (1983), "La chaine tello-rifine (Algerie, Maroc, Tunisie): structure, stratigraphie et evolution du Trias-sic au Miocene (The orogenic belt of the Rif (Morocco) and the Tell (Algeria, Tunisia): structural, stratigraphic, palaeogeographic and tectonic evolution from the Triassic to Miocene)". *Rev. Geogr. Phys. et Geol. Dynamique*, **24**, pp. 201-297.

Yilmaz, P.O. (1984), Fossil and K-Ar data for the age of the Antalya Complex, S.W. Turkey. In *The Geological Evolution of the Eastern Mediterranean* (Edited by Dixon, J.E. and A.H.F. Robertson). *Geol. Soc., London, Spec. Publ.* **17**, pp. 335-347.

Ziegler, P.A. (1988), *Evolution of the Arctic-North Atlantic and the Western Tethys*. Am. Assoc. Petrol. Geol., *Mem.* **43**, 198 p.

Ziegler, P.A. (1987), Late Cretaceous and Cenozoic intra-plate compressional deformations in the Alpine Foreland - a geodynamic model. In *Compressional Intra-Plate Deformations in the Alpine Foreland* (Edited by Ziegler, P.A.). *Tectonophysics*, **137**, pp. 389-420.

Ziegler, P.A. (1990), *Geological Atlas of Western and Central Europe*, Shell Internat. Petrol. Mij. B. V., distrib. Geol. Soc., London, Publ. House, Bath, 239 p.

Zonenshain, L.P., M.I. Kuzmin and L.M. Natapov (1990), *Geology of the USSR - A Plate-Tectonic Synthesis*. Am. Geophys. Union, *Geodynamics Ser.* **21**, 242 p.

Enclosures

Enclosure 1 Paleozoic crustal blocks on Permian base map

Enclosure 2 Mid-Carboniferous Namurian (322 Ma) paleogeography

Enclosure 3 Upper Carboniferous Westphalian A/B (306 Ma) paleogeography

Enclosure 4 Lower Permian Rotliegendes (254 Ma) paleogeography

Enclosure 5 Upper Permian Zechstein (251 Ma) paleogeography

Enclosure 6 Mesozoic crustal blocks on present-day base map

Enclosure 7 Upper Triassic Rhaetian (210 Ma) paleogeography

Enclosure 8 Lower Jurassic Toarcian (179 Ma) paleogeography

Enclosure 9 Middle Jurassic Bathonian (158.5 Ma) paleogeography

Enclosure 10 Lower Cretaceous Aptian (122 Ma) paleogeography

Enclosure 11 Lower Oligocene Rupelian (33.5 Ma) paleogeography

Enclosure 12 Middle Miocene Serravalian (10.5 Ma) paleogeography

Enclosure 13 Lower Pliocene (3.8 Ma) paleogeography